

AN ANALYSIS OF POROUS-PLATE COMBUSTION SYSTEMS

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INTRODUCTION

In the porous-plate combustion system, an unburned gaseous fuel-oxidant mixture is fed into the upstream side of a porous solid. The combustion or reaction zone is near the downstream surface. The variety of possible pore structures and solid materials offers a variety of reaction areas. They include combustion in the gas phase above the solid (a flame), in pores large enough to permit essentially ordinary flames, in pores too small to permit ordinary flames, on the pore surfaces within a catalytic porous medium, and combinations of these.

This paper presents a theoretical analysis of combustion in and above a non-catalytic solid with fine pores. Its purpose is to indicate the limits of steady-state operation of such a system, and the operating characteristics as they depend on flow rate.

The location of the combustion zone is deduced from the model, rather than included in the assumptions. Potentially, the porous plate can operate either as a preheater or as a reactor. In the first case, the incoming gases are heated in the plate and most of the combustion occurs above it. In the other case, most of the combustion occurs in the plate. The characteristics of both mechanisms are of interest here. The quantitative results are necessarily inseparable from the assumed chemical kinetics and physical properties. These have been chosen to correspond to reasonably real systems, but in any case, they demonstrate the types of operating boundaries to be encountered in such systems.

THE HYPOTHETICAL MODEL

The system is defined to be unidimensional, with a semi-infinite porous solid. Within the porous phase, the gas and solid temperatures are equivalent, and the pores are sufficiently fine that the equations applicable to a homogeneous phase can be used. The chemical kinetics are the same within the pores as in the gas phase outside the solid.

The equations to describe the energy and mass transfer in this system are based on those presented by Spalding.¹ To solve the equations, even numerically, a relationship between the local temperature and composition is extremely convenient. In the porous phase, the assumption of no mass diffusion generates this relationship. In the gas region, the assumption of a Lewis number of 1, as originally suggested by Semenov,² serves this purpose.

Furthermore, the formulation of the overall kinetics of the reaction is most conveniently set in terms of mass fraction of the fuel (for a lean system) and the temperature, in the manner used by Spalding.³ The resulting steady-state equations, in terms of reduced variables, are:

For the region outside the solid

$$d^2\tau/dy^2 - d\tau/dy + a^{n,m}/g^2\lambda^2 = 0 \quad (1)$$

$$\alpha = \tau_f - \tau \quad (2)$$

For the porous region

$$r_k d^2\tau/dy^2 - d\tau/dy + \alpha^n \tau^m P/g^2 \lambda^2 = 0 \quad (3)$$

$$\alpha = 1 - \tau + r_k d\tau/dy \quad (4)$$

where

τ = temperature above the feed gas temperature relative to the adiabatic temperature rise

y = distance \times gas specific heat \times gas mass velocity / gas thermal conductivity

α = fuel mass fraction relative to inlet fuel mass fraction

r_k = mean solid thermal conductivity relative to that of the gas

g = mass velocity relative to the adiabatic burning velocity

n = overall order of reaction in terms of fuel fraction

τ^m = temperature dependence of reaction rate

P = porosity of the solid

λ^2 = constant

The interaction of the system with the surroundings occurs only by radiation to and from the porous-plate surface. With this, the conditions at the boundaries are:

$$y = -\infty: \tau = 0, d\tau/dy = 0 \quad (5)$$

$$y = \infty: \tau = \tau_f, d\tau/dy = 0 \quad (6)$$

$$y = 0: \epsilon \tau^s = g(1 - \tau_f) + \epsilon \tau_b^s \quad (7)$$

$$\tau_f = 1 + r_k (d\tau/dy)_{y < 0} - (d\tau/dy)_{y > 0} \quad (8)$$

if y is zero at the surface, τ_f is the final gas temperature, τ_b is the temperature of the surroundings, and $\epsilon \tau^s$ is the radiation law for the solid.

The solution of Equations 1 through 8 for a specified g and τ_b consists of finding a temperature distribution in the porous phase from 3 and 5, and one in the gas phase from 1 and 6, that can be linked up at the surface in accordance with 7 and 8. Two, one, or no solutions may exist, for a given flow rate and surrounding temperature, depending on the operating parameters.

Although reaction occurs in both phases, the solutions correspond to the porous phase acting primarily as a heater, with the major combustion in the gas phase, or to the major combustion occurring in the porous phase. In this paper, these regimes are referred to as preheater and reactor, respectively, to emphasize the role of the porous solid.

The lack of a steady-state solution must imply the impossibility of stable operation for the particular input and surrounding temperature. Also, more than one steady-state solution may exist for any given set of conditions. On the other hand, the existence of a steady-state solution does not necessitate stable operation, since other factors may be involved.

RESULTS

In the primary example used for analysis, values of the parameters are $n=2$, $m=10$, $\epsilon=1.17$, $S=3$ and $P=0.3$. As shown in previous work,³ $m=10$ is appropriate for methane-air systems. For a 105 percent aerated flame with an adiabatic flame temperature of 2190°K, the values for ϵ and S correspond to a black-body radiation law. Two values of r_k were studied, 5 and 20, corresponding to insulating and high-conductivity porous solids, respectively.

In Figure 1, a typical set of temperature distribution curves is presented. Note that Equations 3, 4, and 5 define the temperature distribution in the porous phase with the flow rate as the only operating parameter. The maximum τ increases monotonically with flow rate. Any finite flow rate will yield a porous phase steady-state solution. However, the whole system has a valid steady-state solution only if a surface consistent with Equations 6, 7, and 8 exists. The location of the surface with respect to the temperature distribution of the porous phase depends on the surrounding temperature and on the solution for the gas phase.

In Figure 2, the steady states for a surroundings temperature (τ_b) of 0.4 are shown for $r_k=5$ in terms of the surface and final gas temperatures. This is the behavior of these systems when τ_b is low. The lower input limit is the same for the solid behaving as a reactor or as a preheater. It is not zero if τ_b is greater than zero. The upper input limit of the preheater region corresponds to the situation when all the incoming radiation goes into preheating the gas. Another notable characteristic is the maximum in the surface temperature vs. feed rate curve for preheater operation. Thus, a maximum yield of radiation energy exists for this type of operation.

The choice when there are two possible steady states at a given flow rate presumably is determined by the path to the steady state. If the burner is started cold at a flow rate within the preheat region, it will behave as a preheater. If it is started at a higher rate where the solid is a reactor, a reduction in flow rate would keep the system in that regime. The type of instability which results from a reduction of the flow rate beyond the lower input limit is not known from this analysis. However, the extent of reaction is 46 percent within the solid at the lower limit, which would indicate that the system would go into flashback.

In Figure 3, the characteristics of the same system ($r_k=5$) at high surrounding temperatures are illustrated with $\tau_b=.6$. At low flows, no steady states are possible. The regimes, in order of increasing flow rate, then consist of one in which only preheater behavior is possible, one in which both preheater and reactor behavior is possible, and one in which only reactor behavior is possible. These results imply the existence of two lower limits, depending on operation as a preheater or as a reactor. Again, this type of analysis cannot anticipate the behavior at these bounds, in particular whether the lower limit for the reactor corresponds to a discontinuous transition to preheater behavior or directly to flashback.

The equivalent system, but with a higher relative thermal conductivity for the porous phase, $r_k=20$, is similar to the $r_k=5$ system in most aspects. The separation of the lower bounds for preheater and reactor occurs at lower surrounding temperatures, as shown in Figure 4. At higher temperatures, another type of behavior appears. For $\tau_b=0.6$, (Figure 5) there is a flow region too high for preheater activity and too low for reactor behavior.

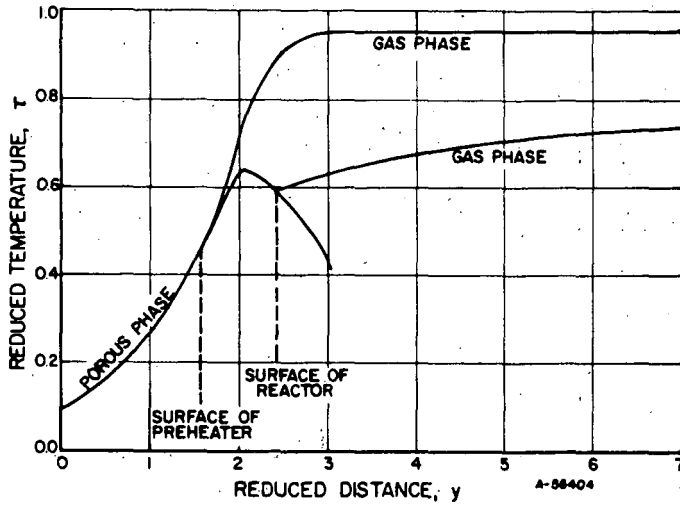


Fig. 1.—TEMPERATURE DISTRIBUTIONS IN POROUS SOLID AND GAS PHASES WITH POROUS PHASE ACTING AS PREHEATER AND AS REACTOR, $\tau_b = 0.4$, $r_k = 5$.

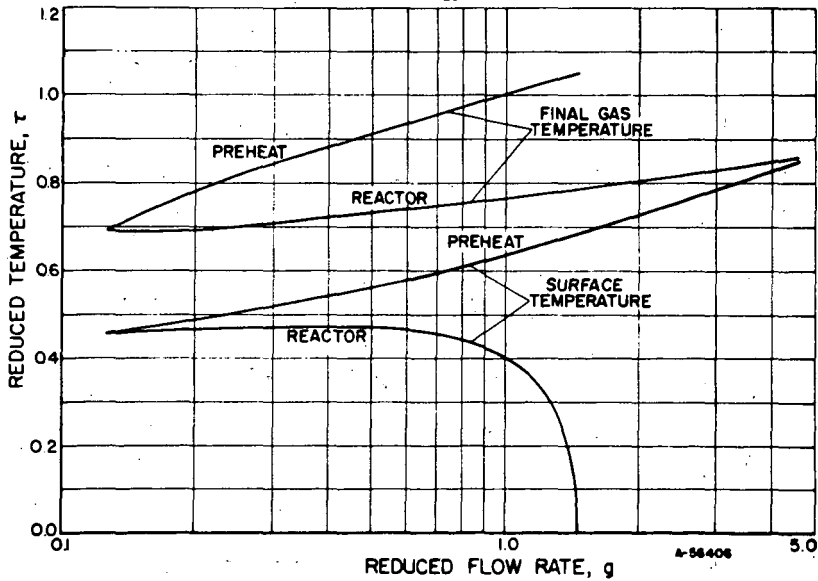


Fig. 2.—FINAL GAS TEMPERATURE AND TEMPERATURE OF THE SURFACE OF THE POROUS SOLID AS FUNCTIONS OF GAS FLOW RATE, $\tau_b = 0.4$, $r_k = 5$.

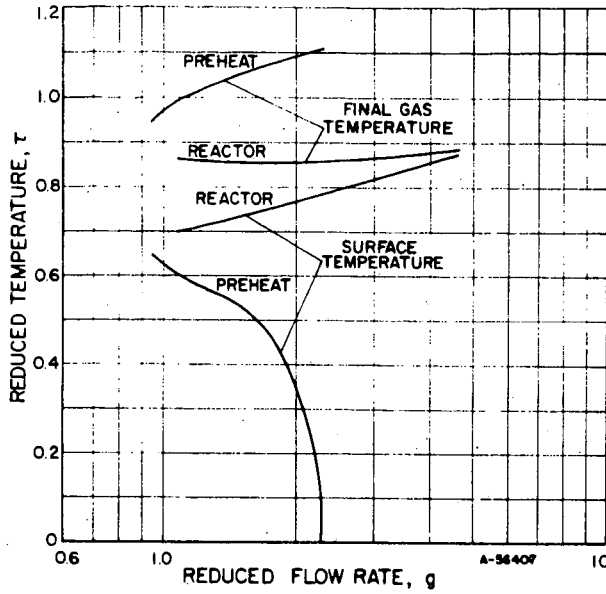


Fig. 3.—FINAL GAS TEMPERATURE AND TEMPERATURE OF THE SURFACE OF THE POROUS SOLID AS FUNCTIONS OF FLOW RATE, $\tau_b = 0.6$, $r_k = 5$.

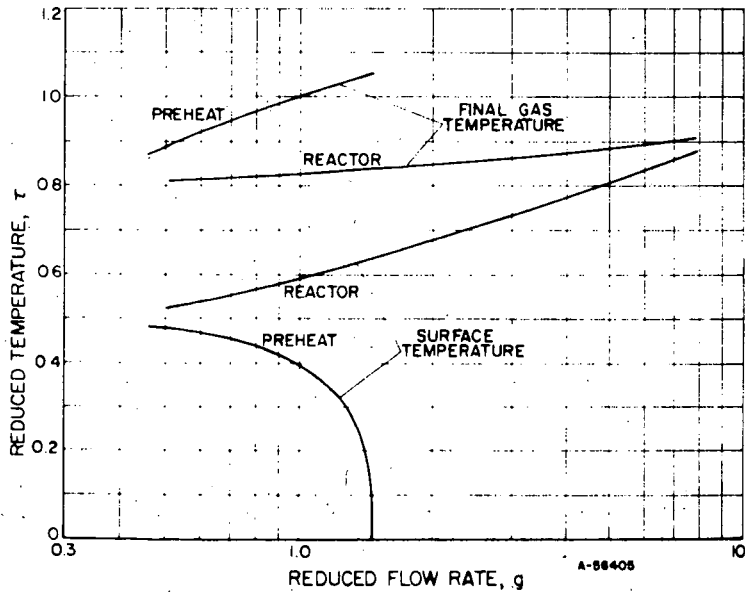


Fig. 4.—FINAL GAS TEMPERATURE AND TEMPERATURE OF THE SURFACE OF THE POROUS SOLID AS FUNCTIONS OF GAS FLOW RATE, $\tau_b = 0.4$, $r_k = 20$.

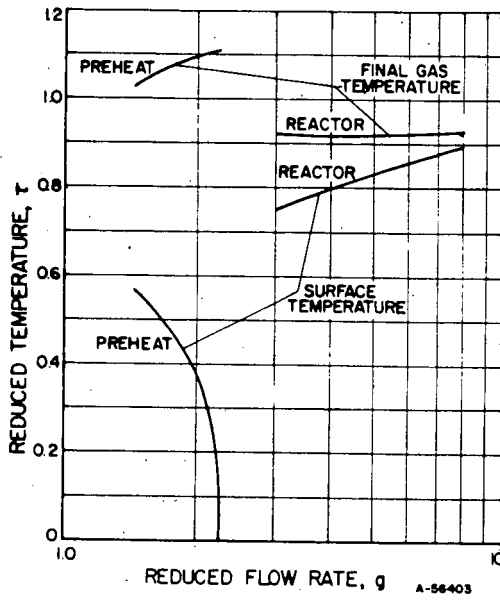


Fig. 5.—FINAL GAS TEMPERATURE AND TEMPERATURE OF THE SURFACE OF THE POROUS SOLID AS FUNCTIONS OF GAS FLOW RATE, $\tau_b = 0.6$, $r_k = 20$.

SUMMARY

The theoretical analysis demonstrates the existence of heat input limits (limits of steady-state operation) for a noncatalytic porous-plate burner. It indicates the relative location of these limits and the effect of the temperature of the surroundings. The analysis also shows the surface temperatures as a function of input and surrounding temperature.

The porous plate can operate in two ways:

- 1) As a preheater — The incoming gases are preheated as they pass through the plate, with most of the combustion occurring above the plate.
- 2) As a reactor — The fuel-air mixture reacts primarily in the plate rather than above it.

Three different input limits for steady-state operation are shown to exist:

- 1) An upper limit for operation as a preheater.
- 2) A lower limit for preheater operation.
- 3) A lower limit for reactor operation.

Limits 2 and 3 can be identical under some conditions.

The porous plate can sometimes act either as a preheater or as a reactor at a given input. In such a case, it may be difficult to visually differentiate between the two mechanisms since the plate surface temperatures are often similar. The appropriate mechanism can be determined most readily by determining the effect of variations in the input rate on the surface temperature.

REFERENCES CITED

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